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A Geospatial Approach for Rooftop Rainwater Harvesting Potential in Hyderabad City, Telangana, India

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Abstract

Hyderabad, a major metropolitan city in Telangana, India, suffers from flash floods and water scarcity issues that are intensified by erratic and extreme weather patterns. A sustainable solution to address urban water scarcity is through Rooftop Rainwater Harvesting (RRWH), especially in rapidly growing cities like Hyderabad. The risk of waterlogging can be considerably reduced in areas with frequent flooding by installing RRWH widely on institutional, commercial, and residential buildings. Large-scale RRWH implementation promotes a change to resilient urban infrastructure, which has the added advantages of reducing flooding and addressing water scarcity. This integrated strategy helps Hyderabad adapt to climate variability and is in line with the goals of sustainable urban planning. The present study aims to explore the potential of rooftop rainwater harvesting in Greater Hyderabad Municipal Corporation (GHMC) using a geospatial approach, with the ultimate goal of contributing to sustainable urban development in the region, addressing water security and flooding through water conservation. Building rooftop areas were estimated using Open Buildings V3 data via Google Earth Engine, and RRWH potential was calculated using Rande's efficiency and Gould and Nissen-Petersen's formula (1999). The results of the study indicate that RRWH potential can fully meet drinking and cooking water demands and significantly supplement domestic uses like bathing and flushing. With 141.21 billion litres /year available, RRWH can meet up to 32.75% of total domestic basic water demand and 29.47% of standard urban water demand, highlighting its critical role in reducing reliance on municipal water and promoting urban water sustainability. Implementing RRWH in densely populated areas can provide supplemental water for domestic use. Large rooftops of domestic and commercial buildings are ideal sites for significant water harvesting, which will reduce water consumption, operational costs, and stormwater runoff through RRWH.

Keywords

Rooftop; Rainwater harvesting; Potential; Geospatial approach

Introduction

Water is an essential resource for life, but it also plays a critical role in regulating the climate on Earth.Changes in land use, such as urbanization and deforestation, alter the balance among water pathways, evaporation, percolation, and runoff (Sterling, Ducharne and Polcher, 2012). These changes affect how water moves through the environment, impacting everything from groundwater levels to local weather patterns. Climate change is creating more extreme weather patterns, and urban development is decreasing land efficiency in holding water, necessitating changes to water management practices (Lako and Kerpaci, 2024). With global warming and increasing water scarcity, the need for innovative and sustainable water management strategies have become paramount, particularly in urban settings (UNESCO World Water Assessment Programme, 2020). Achieving permanent land use compatibility is a fundamental goal in urban and regional planning, essential for fostering sustainable and harmonious communities (Sevelka, 2025). Unregulated land developmental activities result in serious environmental degradation. Working with local communities is important in order to develop solutions that satisfy economic development and environmental conservation (Grefalda *et al*., 2024). Ecological and socio-economic balance preservation, environment restoration, and improvement as well as minimization of risks are the key tasks of modern society supported with sustainable development. (Abdyralieva and Totubaeva, 2024).

Increasing water demand in urban areas has driven the development of non-conventional water supply sources globally, mainly in regions with Mediterranean or semi-arid climates where water scarcity is a significant challenge (Ricart *et al*., 2021). However, rapid urbanization and changes in land use also increase the risk of precipitation extremes in urban areas will pose challenges for urban storm water infrastructure and flooding, as natural water absorption areas are replaced by impervious surfaces, leading to increased runoff and flood vulnerability (Mishra *et al*., 2015). Balancing water conservation, supply, and flood management are essential to create resilient urban environments in the face of these climate challenges. Rainwater harvesting (RWH) is based on the concept of capturing and utilizing rainwater directly at the location where it falls. Rainwater harvesting and conservation is a process of collection of rainwater directly and storing for immediate or later use and groundwater recharge. The purpose is to use the rainwater effectively rather than letting it be wasted by increasing storage of water and decreasing the runoff into rivers, channels or sewers (Hari *et al*., 2018). Rooftop Rainwater Harvesting (RRWH), a decentralized and economic way to supplement water supplies, can effectively address water scarcity. Since they provide significant opportunities to capture water from large surface areas, rooftop rainwater harvesting systems have become increasingly popular. With roofs covering almost half of the city's surface, building rooftops constitute a significant land cover type in urban areas and are therefore ideal for collecting water (Ugai, 2016). Urban flooding can be minimized by collecting rainwater directly from rooftops, which reduces the volume of water that runs off into streets and drainage systems. RWH systems lower the pressure on urban drainage infrastructure by decreasing runoff, which avoids overflow and lowers the risk of flooding during periods of high precipitation.

RWH prevents pollutants from entering water bodies and decreases soil erosion by collecting rainfall before it reaches the surface of the earth. In order to guarantee

effective rainwater collection, storage, and use, particularly in urban areas, the Indian Standard (IS 15797, 2008) offers guidelines for rooftop rainwater harvesting systems. By encouraging sustainable water use, decreasing reliance on municipal water supplies, and tackling issues of urban flooding and groundwater depletion, these guidelines aim to support efficient water management practices in urban areas.

The total amount of rainwater that can be collected at a specific location is called the rainwater potential. Depending on rainfall patterns, the extent of the catchment area within which the rainwater can be harvested, and local weather conditions, this potential can vary. It is important to understand the potential of rainwater in a region, is essential in order to plan efficient rainwater harvesting systems and best practices. The formula by Gould and Nissen-Petersen (1999) is widely used for its reliability in calculating how much rainwater can be harvested from rooftops, based on the parameters such as the area of roof catchment, intensity of rainfall, and the effectiveness of the rainwater collection system. Rainwater harvesting potential has been explored in many studies (Baby, Arrowsmith and Al-Ansari, 2019; Dadhich and Mathur, 2016; Hari *et al*., 2018; Kumar *et al*., 2022; Mouli, Krupavathi and Ganeswara Rao, 2020) using geospatial technologies like Remote sensing and GIS. GIS can make a crucial contribution to Sustainable Development Goals (SDGs) in combination with rainwater harvesting, through its capability to handle large spatial data. The digitization of building roof areas through GIS is a useful technique to estimate the rainwater harvesting potential by calculating the respective areas. This method generally consists in a manual or semi-automatic mapping of rooftop boundaries on high-resolution aerial photographs or satellite images within a GIS software.

Manual digitization involves an extensive amount of effort, time, and money. Automated building footprint extraction using GIS and remote sensing will be more appropriate for a more efficient model building that can determine the RWH potential for large-scale water harvesting projects (Preeti and Rahman, 2021). Automated building footprint extraction is ideal for regional or global use since it provides quick, extensive mapping using satellite imagery. Building footprints become crucial for various applications such as urban planning, disaster response, population estimation, and environmental studies.

In developing areas where there may be few surveys, a large number of informal settlements, and rapid urbanization, this information becomes especially important. Although technical challenges in detecting buildings in such areas, precise footprint data can fill in important knowledge gaps in spatial knowledge (Sirko *et al*., 2021). The main objective of this study is to assess the feasibility of the potential of rooftop rainwater harvesting that could meet different domestic water demands in Hyderabad, Telangana, India, by using geospatial technologies. By employing advanced geospatial technologies such as high-resolution gridded rainfall data, satellite imagery, building footprint data, and GIS analysis, the study identifies and quantifies rooftop rainwater harvesting potential across the Greater Hyderabad Municipal Corporation.

Methodology

Study Area

Hyderabad, the capital of Telangana, is governed by the Greater Hyderabad Municipal Corporation (GHMC), which is situated at latitude 17°21′42″N and longitude 78°28′29″E. With a total area of 650 km^2, GHMC is one of India's biggest metropolitan cities. As of the 2011 census, the population density is 18,480 / km^2 making Hyderabad the nation's fourth most populous city. Hyderabad is located in the southern region of Telangana, in southeastern India, along the banks of the Musi River, a tributary of the Krishna River situated on the Deccan Plateau in northern South India. The topography of GHMC is characterized by a rocky and undulating landscape with gentle slopes and red gravelly soils with an average altitude of 542 m. The city exhibits a tropical wet and dry climate (Köppen Aw), with a hot semi-arid climate (Köppen BSh). The city has distinct seasons, with hot summers, moderate monsoons, and mild winters with an annual mean temperature of 26.6°C. Hyderabad experiences an average annual rainfall of 859.6 mm (33.84 inch) according to the India Meteorological Department (IMD) and global climate records, which presents a significant opportunity to harness this underutilized resource. Existing surface water sources and groundwater reserves in the region have struggled to keep pace with the growing water demands of the city's burgeoning population, leading to a precarious situation that necessitates immediate action. There is a significant spatial variability in the spatial distribution of rainfall in Hyderabad with some locations recording increasing intensities and others experiencing stable or decreasing values. These topographically based differences are influenced by land use transition, urbanization, microclimatic elements (Hari and Kasa, 2024).

Water scarcity and frequent urban flooding are the two major challenges Hyderabad suffers from, which are exacerbated by impermeable surfaces, rapid urbanization, and lack of suitable drainage infrastructure. Heavy rains during the monsoon season frequently overflow the drainage system, resulting in flash floods that cause property damage and disruption to daily life. Simultaneously, extended dry spells and rising water demand strain the city's limited water resources. Integrating Rooftop Rainwater Harvesting can alleviate pressure on stormwater systems by diverting runoff, thereby reducing flood risk while contributing to sustainable water supply management. The city's expanding metropolitan area is putting pressure on its public service facilities, particularly in handling water and sanitation services. The integration of geospatial technologies in assessing the potential for RRWH has become an essential aspect of sustainable urban planning. As the water crisis intensifies, it is necessary to reform the water management system and revive traditional methods. Scientific and technological studies should be conducted to assess the current situation and recommend effective measures for restoring traditional systems and knowledge.

Figure 1 depicts the geographical location as well as the locations of the rainfall grids within GHMC that were taken into account for the present study.

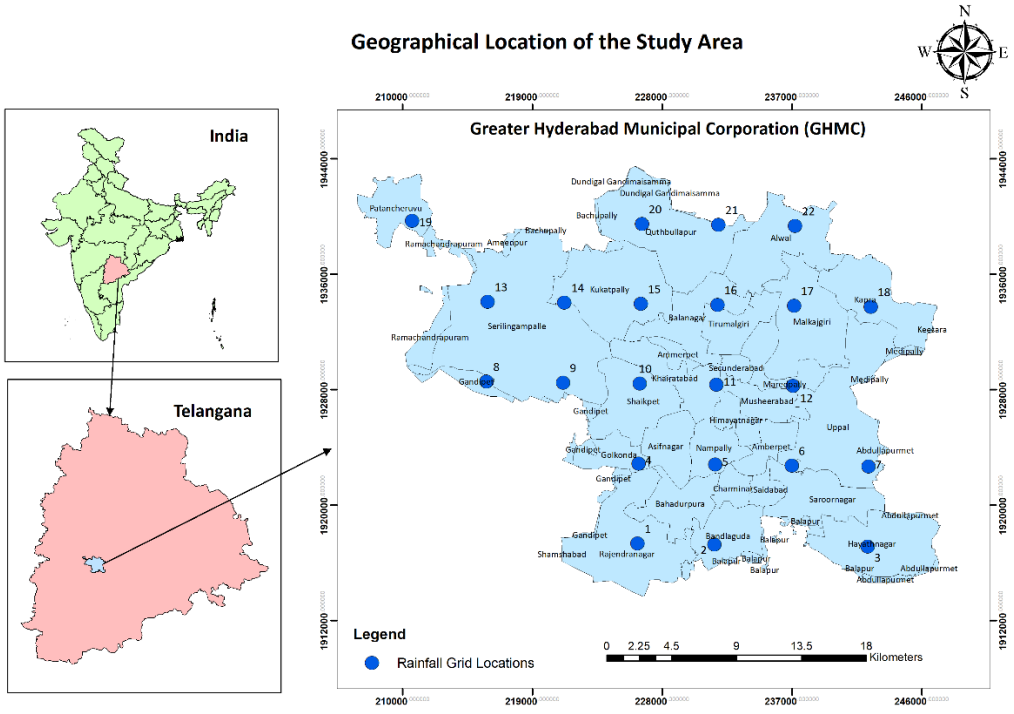

Figure 1: Map of the study area highlighting the Greater Hyderabad Municipal Corporation (GHMC)

The methodology adopted in this study integrates geospatial data processing and hydrological modeling to estimate the rooftop rainwater harvesting potential within the GHMC limits. The study area was delineated with the official administrative boundary of GHMC. Using Google Earth Engine (GEE), high-resolution building footprint data were extracted from the Open Buildings V3 dataset. The building footprints were extracted to the GHMC administrative boundary and processed further for geometry correction using ArcGIS, including removal of overlapping features. To ensure accurate area measurements, the vector data were reprojected to an appropriate coordinate system. Individual Building rooftop areas were then calculated using geometry tools in ArcGIS, and a rooftop area map was generated. Google Earth imagery was used for verifying rooftop areas at specific locations within the GHMC limits as part of the validation process.

Rainfall data were obtained from the CHIRPS daily gridded precipitation dataset from 1990 to 2020. The raster files of rainfall were clipped to the GHMC boundary and converted to vector data format. The files are reprojected to local datum and the average annual rainfall of the study area was computed. The rooftop rainwater harvesting potential was determined through the Gould and Nissen-Petersen (1999) formula by considering the concrete rooftops in the GHMC by adopting a runoff coefficient of 0.95. The annual water demand was calculated using the GHMC population of 2021 and standard per capita water consumption rates (LPCD). The estimated RRWH volume was then compared with domestic water demand to assess the potential contribution of RRWH to urban water security. The overall methodological framework is presented in figure 2.

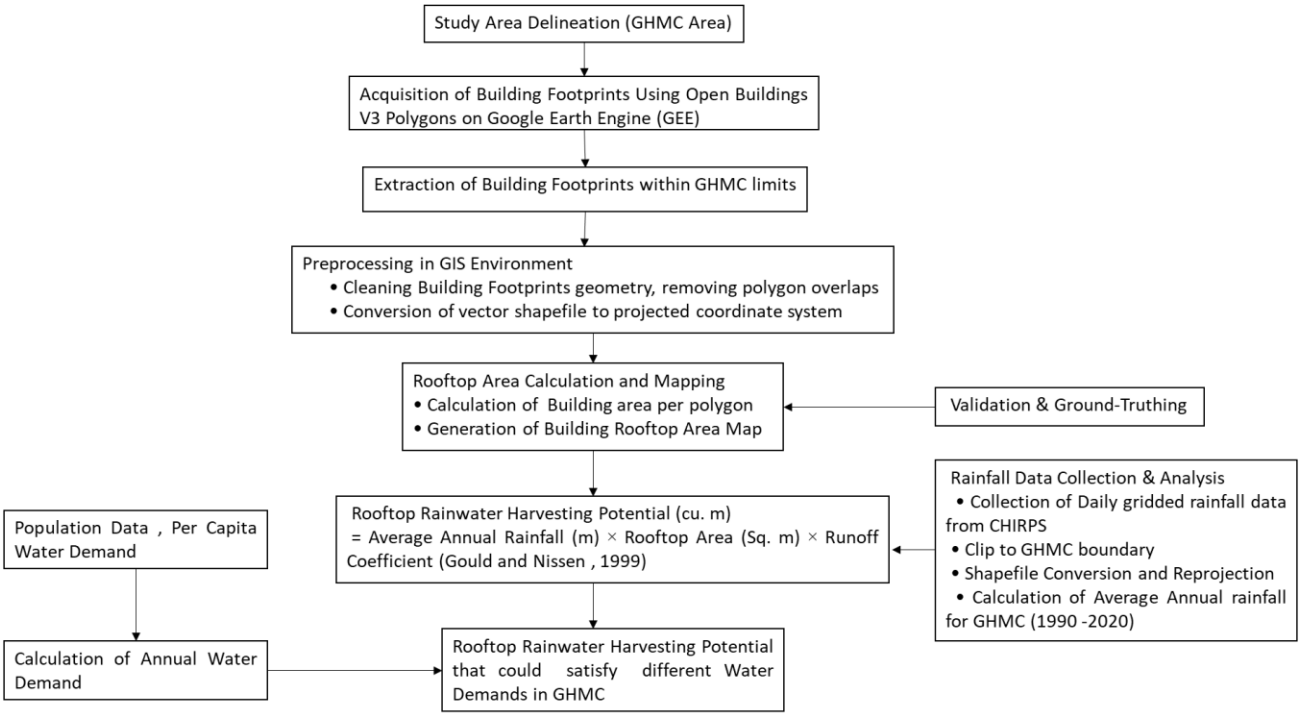
Study Area Delineation (GHMC Area)
Acquisition of Building Footprints Using Open Buildings V3 Polygons on Google Earth Engine (GEE)
Extraction of Building Footprints within GHMC limits
Preprocessing in GIS Environment
• Cleaning Building Footprints geometry, removing polygon overlaps
• Conversion of vector shapefile to projected coordinate system
Rooftop Area Calculation and Mapping
• Calculation of Building area per polygon
• Generation of Building Rooftop Area Map
Validation & Ground-Truthing
Rainfall Data Collection & Analysis
• Collection of Daily gridded rainfall data from CHIRPS
• Clip to GHMC boundary
• Shapefile Conversion and Reprojection
• Calculation of Average Annual rainfall for GHMC (1990 -2020)
Rooftop Rainwater Harvesting Potential (cu. m)
= Average Annual Rainfall (m) × Rooftop Area (Sq. m) × Runoff Coefficient (Gould and Nissen , 1999)
Population Data , Per Capita Water Demand
Calculation of Annual Water Demand
Rooftop Rainwater Harvesting Potential that could satisfy different Water Demands in GHMC

Figure 2: Flowchart representing the methodology adopted in the study

Results and Discussion

Building Footprint Extraction and Rooftop Area Estimation

The current study uses a geospatial approach to determine rooftop rainwater harvesting potential in Hyderabad city, Telangana. Initially, the study area boundary corresponding to the Greater Hyderabad Municipal Corporation limits was delineated using administrative spatial data. Building footprints for the city are then acquired from the Open Buildings V3 Polygons dataset using Google Earth Engine (Gorelick *et al.,* 2017). The Open Buildings dataset comprises building footprints derived from high-resolution satellite imagery with a spatial resolution of 50 centimeters. The building footprints are clipped to the GHMC boundary and pre-processed in the ArcGIS environment to remove errors such as overlaps and incomplete polygons. The building footprint shapefiles, initially referenced in EPSG:4326 (WGS 84), were transformed to the projected coordinate system EPSG:32644 (WGS 84 / UTM Zone 44N) to facilitate accurate area computations in metric units. Making use of the Calculate Geometry tool in ArcGIS, rooftop areas of a total of 1505840 buildings were computed for each polygon in square meters, resulting in a cumulative rooftop area of 172236255 m². The final rooftop area map enables detailed analysis for estimating the rainwater harvesting potential of Hyderabad. The overview of extracted building footprints and the building rooftop area map is generated and presented in figures 3 and 4.

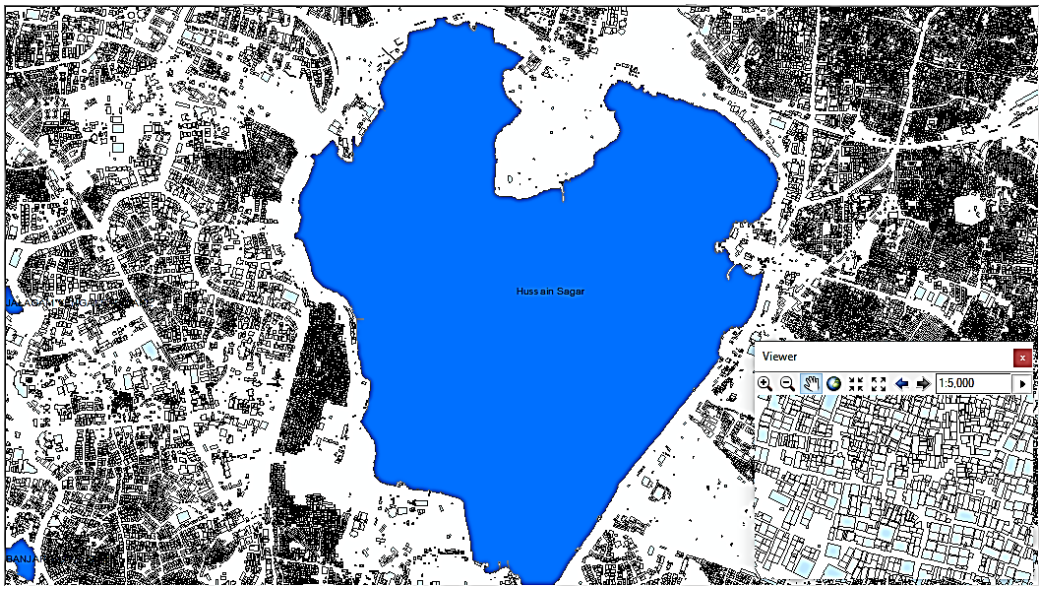

Figure 3: Overview of Extracted Building Footprint

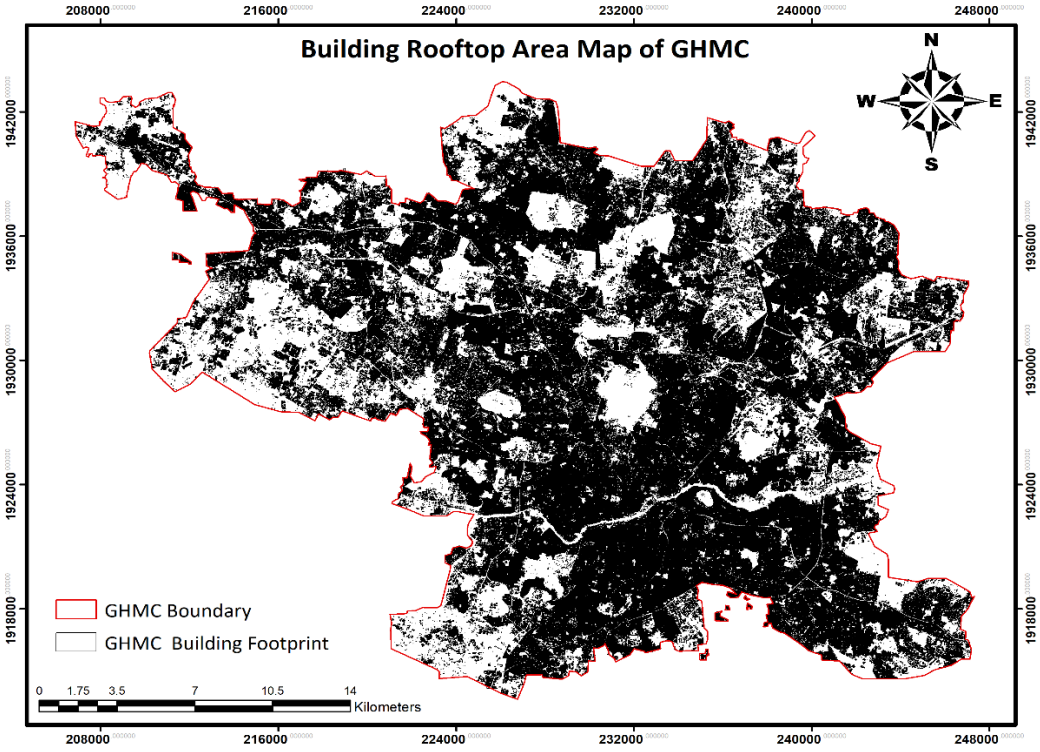

Figure 4: Building Rooftop Area Map of GHMC

Rainfall Data Collection and Analysis

Daily rainfall data in point grid format from 1990 to 2020 were acquired from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) database (https://www.chc.ucsb.edu/data/chirps), which provides gridded rainfall estimates at a spatial resolution of 0.05°. These rainfall data points were clipped to the Greater Hyderabad Municipal Corporation boundary using GIS. Annual rainfall time series were computed for each grid point, and the processed data were converted into shapefile format and reprojected to the UTM projection. The average annual rainfall for all 22 locations within the GHMC area was calculated for the 1990 - 2020 period. Table 1 presents the average annual rainfall of Hyderabad City by location from 1990 to 2020 in mm. The results indicate that GHMC experienced average annual rainfall ranging from 841.76 mm to 885.29 mm, highlighting significant spatial variability in rainfall distribution across the region.

Table 1: Average Annual Rainfall of Hyderabad City by location from 1990 to 2020 in mm

Rainfall Grid No.	*Latitude*	*Longitude*	*Average Annual Rainfall in mm (1990 -2020)*
1	17.325	78.425	847.83
2	17.325	78.475	852.65
3	17.325	78.575	870.85
4	17.375	78.425	841.76
5	17.375	78.475	850.87
6	17.375	78.525	867.66
7	17.375	78.575	882.28
8	17.425	78.325	862.48
9	17.425	78.375	856.49
10	17.425	78.425	871.47
11	17.425	78.475	860.91
12	17.425	78.525	868.44
13	17.475	78.325	860.89
14	17.475	78.375	854.52
15	17.475	78.425	849.25
16	17.475	78.475	861.29
17	17.475	78.525	874.59
18	17.475	78.575	883.32
19	17.525	78.275	873.54
20	17.525	78.425	856.38
21	17.525	78.475	866.00
22	17.525	78.525	885.29
	Average		863.58

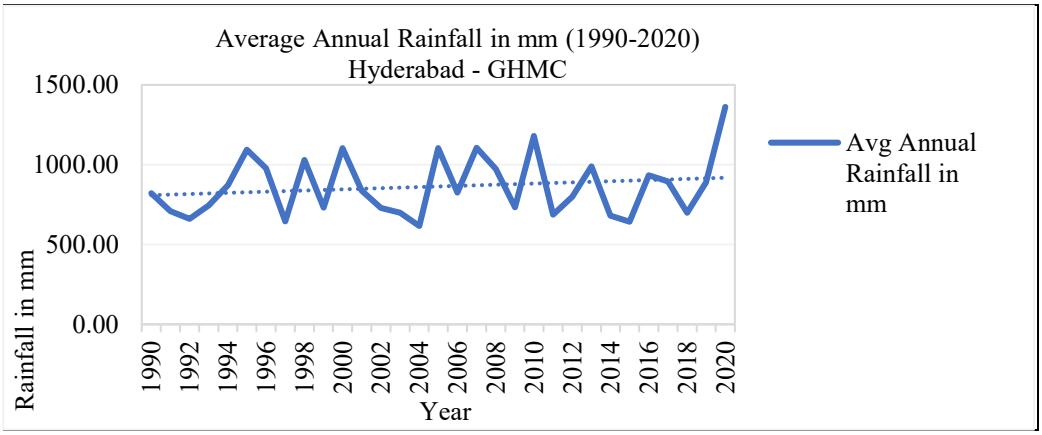

Figure 5: Average Annual Rainfall of GHMC in mm (1990-2020)

The study area exhibited an increasing trend in annual average rainfall, with the lowest recorded value of 616.06 mm in 2004 and the highest reaching 1362.04 mm in 2020. The Greater Hyderabad Municipal Corporation recorded an average annual rainfall of 863.58 mm between 1990 and 2020. Figure 5 presents a graphical representation of the average annual rainfall during this period.

Estimation of Rooftop Rainwater Harvesting (RRWH) Potential

Rooftop Rainwater Harvesting (RRWH) potential in the GHMC area was estimated using the widely accepted method proposed by Gould and Nissen-Petersen (1999). The potential volume of harvestable rainwater was calculated using the formula:

RRWH Potential (m^3) = Average Annual Rainfall (m) × Rooftop Area (m^2) × Runoff Coefficient
= 0.863 × 172236255 × 0.95
= 141,207,894 m^3 = 141.21 billion litres = 141207894000 litres

In the present study, the average annual rainfall was considered to be 0.863 meters, based on 31 years of climatic records of GHMC from 1990 to 2020. The effective rooftop area, estimated from building footprint data extracted using Open Buildings V3 Polygons via Google Earth Engine, was 172,236,255 square meters. A runoff coefficient of 0.95, suitable for impervious concrete rooftops and RCC rooftops, was used to account for collection efficiency (IGBC 2019). By applying these values to the established formula by Gould and Nissen-Petersen (1999), the total annual rooftop rainwater harvesting potential for the study area was calculated to be 141,207,894 cubic meters, equivalent to 141.21 billion litres or 141207894000 litres.

Analysis of Water Demand and Rainwater Harvesting Potential

The annual water demand in the Greater Hyderabad Municipal Corporation region was estimated using standard per capita water consumption benchmarks prescribed by the Central Public Health and Environmental Engineering Organisation (CPHEEO, 2019) and MoHUA guidelines.

As projected by Census2011.co.in, the population of Hyderabad city in 2021 is estimated to be approximately 8,751,000 (Census2011.co.in, 2025), was considered for the analysis. The annual demand in each category was computed using the formula:

Annual Water Demand (m^3) = Population × Per Capita Water Demand ×365

Table 2: Annual Domestic Water Demand and Contribution of Rainwater Harvesting Potential

S. No.	*Water Demand Sector*	*Per Capita Water Demand (LPCD)*	*Annual Water Demand (Billion Litres / Year)*	*RRWH Contribution (%)*
1.	Drinking	5	15.96	884.22%
2.	Cooking	5	15.96	884.22%
3.	Bathing	55	175.67	80.38%
4.	Toilet flushing	30	95.82	147.37%
5.	Washing of clothes	20	63.88	221.06%
6.	Washing of utensils	10	31.94	442.11%
7.	House cleaning	10	31.94	442.11%
8.	Total Domestic - Basic need	135	431.70	32.75%
9.	Domestic - Standard Urban / Metropolitan Cities	150	479.11	29.47%

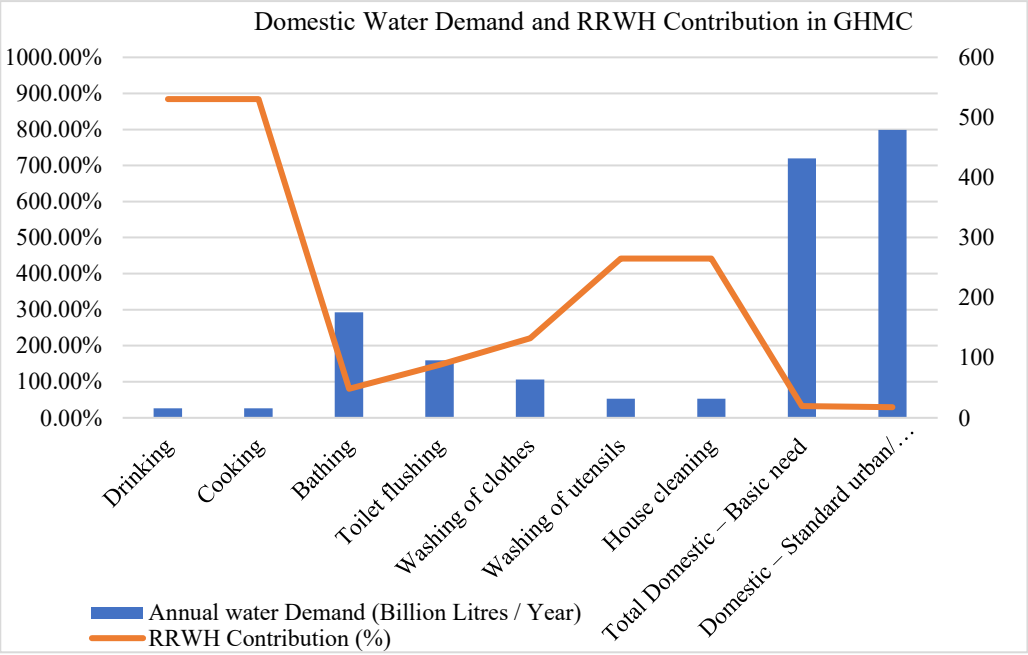

Figure 6: Rooftop Rainwater Harvesting Potential that could satisfy different Water Demands in GHMC

Per Capita Rainwater Harvesting Potential

The per capita rainwater harvesting potential is calculated by dividing the total annual volume of rainwater that can be harvested from rooftops by the total number of people living in the area. To estimate how much harvested rainwater is available per person per day, the annual per capita potential is further divided by 365 days.

Per Capita RRWH Potential (LPCD) =
(Rooftop Rainwater Harvesting Potential) / (Population × 365)
= (141207894000) / (8,751,000 × 365) = 44.21 LPCD

The assessment of domestic water usage across various sectors highlights significant insights into water consumption patterns and the potential of rainwater harvesting as a supplementary source. Table 2 presents the per capita water demand, annual water demand, and the RRWH contribution percentage across typical domestic usage sectors. Figure 6 represents the Rooftop Rainwater Harvesting Potential that could satisfy different Water Demands in GHMC. The analysis reveals that the Rooftop Rainwater Harvesting potential in the Greater Hyderabad Municipal Corporation area is approximately 141.21 billion liters per year. This supply corresponds to a Per Capita Rainwater Harvesting Potential of 44.21 litres per day for the 2021 population of 8.75 million. The findings indicate that while drinking and cooking water needs are minimal, each accounting for only 5 LPCD and about 15.96 billion litres annually, the potential of RRWH in these sectors is exceptionally high, exceeding 880%. This suggests that rainwater can not only meet but vastly surpass the demand in these essential categories, making it a reliable and sustainable alternative for potable uses, provided adequate treatment is ensured.

Among high consumption categories, bathing and toilet flushing dominate, requiring 55 and 30 LPCD, respectively. The annual water demands for these sectors are substantial, 175.67 and 95.82 billion litres, respectively. However, the RRWH contributions for these are comparatively lower at 80.38% and 147.37%, yet they remain significant. These figures emphasize the need for optimized use and integration of RRWH, particularly in retrofitting existing plumbing systems for non-potable uses like toilet flushing and bathing.

Water used for washing clothes, utensils, and house cleaning, while moderate in volume, shows very high RRWH contributions ranging from 221% to 442%. These activities, which can tolerate water of lower quality standards, offer considerable scope for direct utilization of harvested rainwater without extensive treatment, thus reducing reliance on municipal supplies. When considering the total domestic basic need (135 LPCD), the RRWH potential satisfies approximately 32.75%, and 29.47% of the needs for standard urban/metropolitan water usage (150 LPCD). This highlights that while RRWH alone cannot meet the entire urban water demand, it holds immense potential to supplement and reduce the dependency on traditional water supply systems, especially for low and moderate use categories, highlighting its significant role in urban water sustainability.

Conclusion

Rainwater harvesting has been proven to be a fundamental and cost-effective solution to the water crisis and climate adaptation. It is an effective tool for a society aiming to strengthen its climate resilience and ensure water availability to its facilities. To promote effective sustainable RWH systems, it is important to recognize the significance of rainwater and by so doing formulate appropriate systems to meet the regional demands and climate variability. Ultimately, RWH helps in water security and resilience through better infrastructure planning, management of resources, and optimum storage. The present study examines the application of the geospatial approach to Rooftop Rainwater Harvesting in Greater Hyderabad Municipal Corporation, emphasizing its advantages, techniques and potential opportunities for sustainable urban development. This research proposes a comprehensive framework by integrating Geographic Information Systems and Remote Sensing to offer enhanced water sustainability in urban settings. The results demonstrate that non-potable water demands like toilet flushing, gardening, and cleaning can significantly be satisfied through RRWH. The water collected can also serve drinking and cooking purposes with appropriate treatment. This technique provides a cost-effective and sustainable solution that is well-suited to densely populated areas. Large-scale rainwater can be collected efficiently utilizing large rooftops on such buildings as schools, hospitals, and governmental offices. Besides these, RRWH can be used to help institutions and business organizations to reduce their water bills and operating costs by lowering the pressure on the municipal water supply.

RRWH adoption can also lead to increased citizen engagement, which would make way to better-balanced and community-based water management. Regional nonprofits and individual stakeholders have a chance to develop specialized water conservation initiatives cooperating with the local communities in respect to the hydrogeological and sociological features of the area. Such a strategy provides a significant chance to connect the water managers and the community by joint action that leads ultimately to the collaborative water management.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*
Conceived and designed the research or analysis	Yes	No
Collected the data	No	No
Contributed to data analysis and interpretation	Yes	Yes
Wrote the article/paper	Yes	Yes
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Editing of the article/paper	No	Yes
Supervision	No	No
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